Technology Development for the Constellation-X Spectroscopy X-Ray Telescope

Robert Petre[*1], John Lehan[1,2], Stephen O'Dell[3], Scott Owens[4], Paul B. Reid[5], Timo Saha[4], Jeff Stewart[6], William D. Jones[3], William Zhang[1]
[1]X-ray Astrophysics Laboratory, Code 662, NASA / GSFC, Greenbelt, MD 20771 USA
[3]Universities Space Research Association
[2]Optics Branch, Code 551, NASA / GSFC, Greenbelt, MD 20771 USA
[4]Space Science Department, NASA / MSFC, Huntsville, AL 35812 USA
[5]Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138 USA
[6]Mechanical Systems Branch, Code 543, NASA / GSFC, Greenbelt, MD 20771 USA

ABSTRACT

The Constellation-X Spectroscopy X-ray Telescope (SXT) is a large diameter, high throughput, grazing incidence imaging mirror system, designed to perform high sensitivity spectroscopy of cosmic X-ray sources in the 0.2-10.0 keV band. The baseline effective area requirement is ~3 m^2 at 1 keV. The system-level angular-resolution requirement is a 15-arcseconds half-power diameter, with a 5-arcsecond goal. The effective area is attained through a modular design, involving the nesting of many confocal, thin-walled Wolter I mirror segments. Considerable progress has been made in developing thin, thermally formed, glass mirror substrates that meet or better the angular-resolution requirement. Several approaches to mounting and aligning reflector segments into a mirror system are under investigation. We report here on the progress of the SXT technology development program toward reaching the performance goals.

Keywords: X-ray mirrors, Constellation-X

1. INTRODUCTION

Constellation-X is NASA's next major X-ray observatory. Its science goals include addressing questions central to NASA's Beyond Einstein program, including, "What happens to matter close to a black hole?", and "What is Dark Energy?" These questions are addressed using high-resolution, high-throughput, imaging X-ray spectroscopy in the 0.2-10.0 keV band and broad band imaging spectrophotometry across the 0.2-60 keV band. The sensitivity of Constellation-X for high-resolution spectroscopy will be 25 to 100 times higher than previous missions. The science goals of the mission have been summarized in reference 1.

The heart of Constellation-X is the Spectroscopy X-ray Telescope (SXT) mirror. Reaching the sensitivity envisioned for Constellation-X places ambitious requirements on the SXT mirror: an effective area of ~3 m^2 at 1 keV and an angular resolution of 12.5 arc seconds half power diameter (HPD). The critical performance requirements listed in Table 1 have not changed since the inception of the program, but a careful reexamination of the science goals in the light of Chandra and XMM-Newton findings is likely to drive the mission to a larger effective area (~5 m^2) and higher angular resolution (4 arc seconds HPD to allow a 5 arc second system resolution).

As no previous X-ray mirror technology lends itself to meeting these requirements, the Constellation-X project has engaged in a long-term program to develop a suitable approach. This has been the subject of numerous prior publications[2-6]. Briefly, a modular approach has been adopted for the SXT mirror, incorporating tightly nested, thin glass mirror segments. The glass segments are shaped by thermal forming, and an X-ray reflecting surface applied by epoxy replication. This approache maximizes the throughput and minimizes the areal density. It also facilitates mass production of many identical mirror elements, thus keeping cost to a minimum.

[*] robert.petre-1@nasa.gov; phone 301-286-3844; fax 301-286-0677

Table 1
SXT mirror requirements

Bandpass	0.25-10.0 keV	
Effective area (per mirror)		
@0.25 keV	35,000 cm^2	Total for mission (1-4 mirrors, depending on configuration)
@1.25 keV	33,000 cm^2	0.25 keV area for losses due to grating and detector inefficiency
@6.0 keV	6,9000 cm^2	
Angular resolution	12.5"HPD	Consistent with observatory HPD of 15 arc seconds.
	4" HPD goal	Consistent with observatory HPD goal of 5 arc seconds
Field of view	2.5 arc minutes	Defined by detector field of view
		>90 % of on-axis effective area at 1.25 keV across field of view

Over the past year, significant developments have occurred both within the Constellation-X project, and the SXT technology development. A substantial scaling back of funding led to an examination of new spacecraft configurations[7]. The modularity of the SXT approach makes it suitable for all the alternative configurations that have been considered. At the same time, the reduced funding forced the SXT team to emphasize on component development, largely using existing facilities, over prototype development or system studies. This has proven extremely beneficial in that a number of fundamental technical issues regarding mirror fabrication and mounting have been solved.

2. MIRROR FABRICATION

We have made significant progress in all aspects of mirror fabrication. The accompanying paper by Will Zhang explains in detail the progress that has been made.[8] Here we present a summary.

The GSFC Optics Branch has developed a figuring approach for 50 cm scale Wolter I mandrels. Full surface of revolution mandrels are figured. A total of four mandrels have been figured, each with an rms figure error of ~2 arc seconds. These mandrels have allowed us to test our prediction that the mandrel surface quality limits the quality of the mirror surfaces.

A number of improvements have also been incorporated into the mirror substrate forming process. These include a new heating/cooling cycle to insure complete annealing of the substrate, introduction of a smoother, more durable release layer, substantial reduction of surface contaminants from both the ambient environment and the oven interior, and control of the gas composition within the oven to control thermal conduction.

The most important result of these improvements is that the formed substrates follow the mandrel to very high precision. Moreover, the process is highly reproducible. We have replicated 20 or more essentially identical reflector pairs from a mandrel pair without reworking the mandrel. The success rate is essentially 100 percent. With the correct Wolter figure imparted, and mid-frequency roughness controlled, we are producing substrates by heat forming that meet the Constellation-X requirement at all spatial frequencies. We have therefore eliminated the necessity for epoxy replication. This saves the cost of an additional set of mandrels, the complexity of additional production steps, and the difficulty of dealing with a potentially unstable optical surface and a bilayer with different coefficients of thermal expansion.

In Figure 1 we show contour plots from 2-D scans of a recent mirror segment, as measured, and with an average axial profile of the mandrel subtracted. The residual rms error is 0.3 μm. The most significant remaining features are due to surface contaminants (dust). This error represents an upper limit, as this method does not take into account known azimuthal asymmetries on the mandrel.

In Figure 2, we show power spectral density (PSD) curves for a recent segment without epoxy, and a very good epoxy replicated segment from a year ago. The recent segment shows lower power at the lowest spatial frequencies, higher power at spatial frequencies corresponding to wavelengths between 0.3 and 3 cm, and is virtually indistinguishable from the replicated mandrel at high spatial frequencies. The differences on scales larger than 3 mm, both positive and negative, are ascribable to the mandrel. At the low spatial frequencies, replication does not

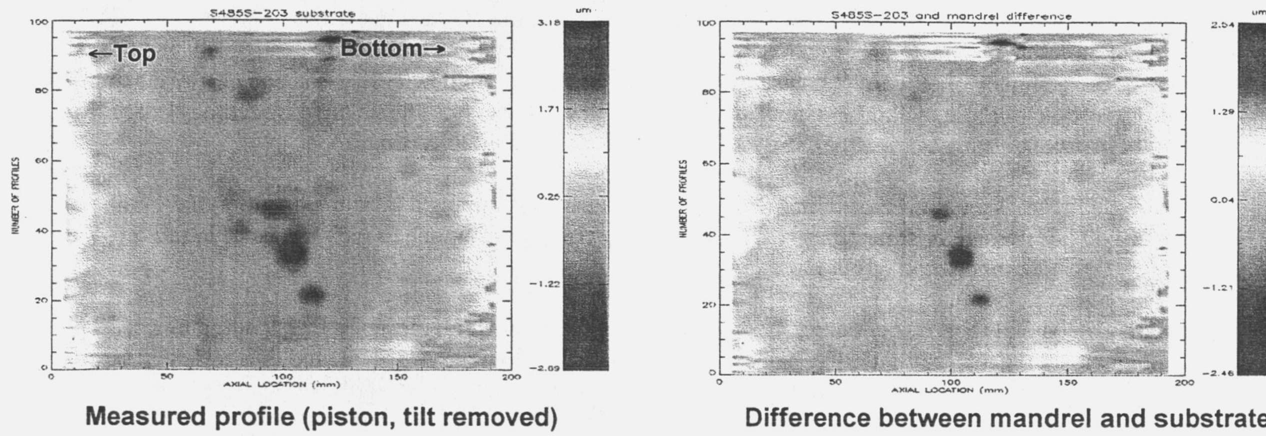

Figure 1: Two-dimensional profile of a mirror segment, without (left) and with (right) average axial mandrel profile removed. Most significant residual features are due to surface impurities (dust).

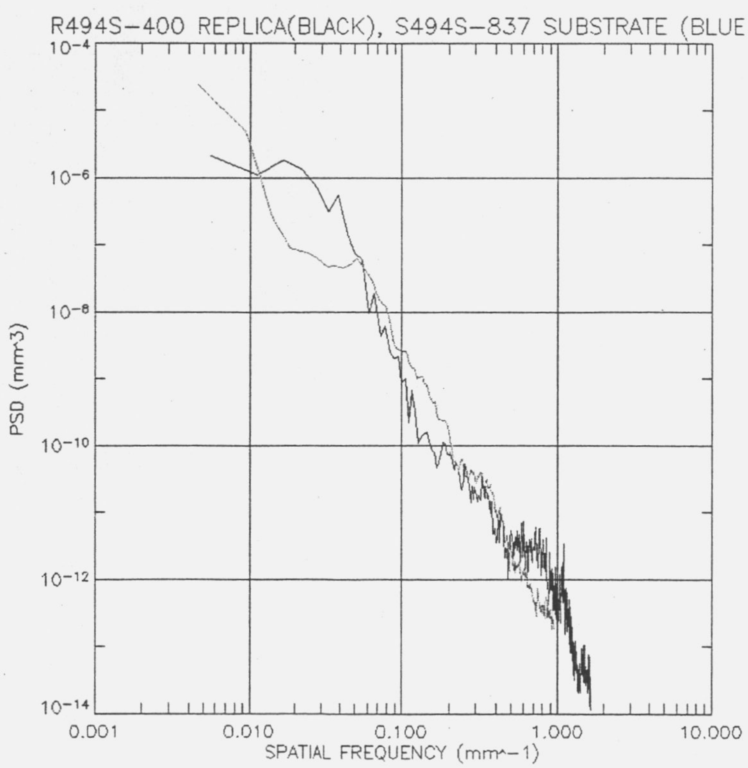

Figure 2: Power spectral density plot of epoxy coated mirror segment produced a year ago using an unfigured mandrel, and a recent segment formed using a figured mandrel, without epoxy. The unreplicated mandrel has better performance at low spatial frequencies, where figure dominates, and is indistinguishable from the replicated segment on spatial scales less than ~3 m.

3. METROLOGY

cover up features introduced by the forming mandrel. At the middle spatial frequencies, the figured forming mandrel surface is known to have a periodic term, which is transferred to the substrate during heat forming. Despite this excess power in the 0.3-3.0 cm band, this mirror substrate meets the Con-X figure requirement.

Another area in which progress has been made is metrology. Metrology of the mirror segments is challenging, and some measurements require approaches as innovative as those for making the mirrors. Our emphasis has been on determining the three dimensional shape of a freestanding mirror segment. In Table 2 we list the measurements performed on segments, the requirements on those measurements, the device currently being used, and the accuracy attained. The accuracy of all current measurement techniques on the rigid mandrels is adequate. When applied to the mirrors, some of these methods are not sufficiently accurate, however. This relative inaccuracy arises from the difficulty in holding or measuring the flimsy substrate material without distorting it.

Some of the methods are time consuming. For instance, manually mapping a mirror substrate surface using a dense series of 1-D interferometer scans takes several hours. We therefore continue to seek means of improving the accuracy, reliability and speed of our metrology.

The most crucial and most difficult measurement is the sag (2nd order curvature) of a freestanding mirror. This measurement is crucial because the sag is the leading term in determining the figure, and thus how well a mirror pair focuses. It is difficult because the primary gravity (and stress) induced distortion term is also second order. We have observed that a slight axial tilt of the mirror from vertical dramatically changes the sag term (it can in fact cause the ends of the mirror to bow convex).

Table 2
Current Mandrel and Mirror Segment Metrology Capabilities

Error Term	Units	specification	Metrology Uncertainty (Max)	Metrology Method (Mandrel)	Precision Achieved (Mandrel)	Metrology (Substrate)	Precision Achieved (Substrate)	Note
Ave Radius Error	μm	<10	3.2	CMM	2	STIL CCMM (non-contact cylindrical CMM)	(16)	1,3
Cone Angle Deviation	arcsec	<10	3.2	CMM	5	STIL CCMM & DI CGH	(15)	1,3
ΔΔR (RMS)	arcsec	<0.6	0.2	CMM	0.6	STIL CCMM & CDA	(1.5) –CCMM (0.3)-CDA	1,3
Roundness or azimuthal error	μm	<4	1.3	CMM	0.3	STIL CCMM	(7)	1,3
Axial sag error	μm/m^2	<12	13	MiniFiz (Fizeau Interferometer)	3	MiniFiz	7	1
Axial slope irregularity (RMS)	arcsec	<1	0.3	MiniFiz	0.35	MiniFiz	0.35	
Midfrequency Errors (RMS)	nm	<1.3	0.4	Bauer200	0.3	Bauer200	0.5	2
Microroughness (RMS)	nm	<0.5	0.1	MicroXAM (Mireau Inteferometer)	0.1	MicroXAM	0.1	
Notes								
1	Accuracy currently limited by mounting.							
2	Needs an independent verification of accuracy.							
3	Numbers in parentheses () are preliminary estimates based on a small sample.							

4. MOUNTING AND ALIGNMENT

As with the work on mirror segments, our mounting and alignment efforts have concentrated on components. Our goal has been to develop a "proof of concept" approach: demonstrating that it is possible to align one or more pairs of mirror segments to the required accuracy, without distorting them. Given the flimsy substrates and the required submicron accuracy, this is a challenging task. Further, we prefer to find a method that requires as few iterations as possible, and one that can in principle lend itself to automation.

The promising approach we have pursued over the past year involves piezoelectric actuators. Such devices, if correctly constructed, can provide both the necessary accuracy and range of motion. Bidirectional devices can be fabricated, making it possible to adjust the segment either radially inward or outward. A bidirectional piezoelectric actuator designed specifically for this application is depicted in Fig. 3.

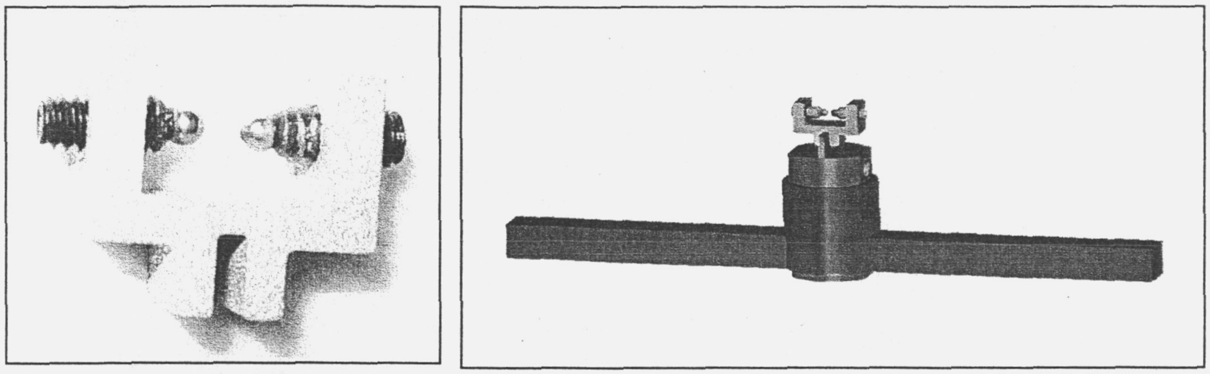

Figure 3: (Left) A bidirectional piezoelectric actuator designed to manipulate the radial position of a mirror segment. The crystal is the gray part. The screws with rounded fronts serve as contact points with the segment. (Right). A schematic of the piezoelectric actuator mounted in a radial support brace. The mirror segment is held by five such braces front and rear.

We are also using a decidedly non-flightlike mirror housing. A stiff structure has been cut out of a solid titanium block. The housing is designed to hold only a small number of mirrors with diameter near 50 cm. Using titanium minimizes the difference between the coefficient of thermal expansion of the glass and that of the housing. The thick structure minimizes the distortions in the mirror due to the housing so that the shape of the glass dominates the errors. The test housing, with a mirror and the piezoelectric actuators installed, is shown in Fig. 4.

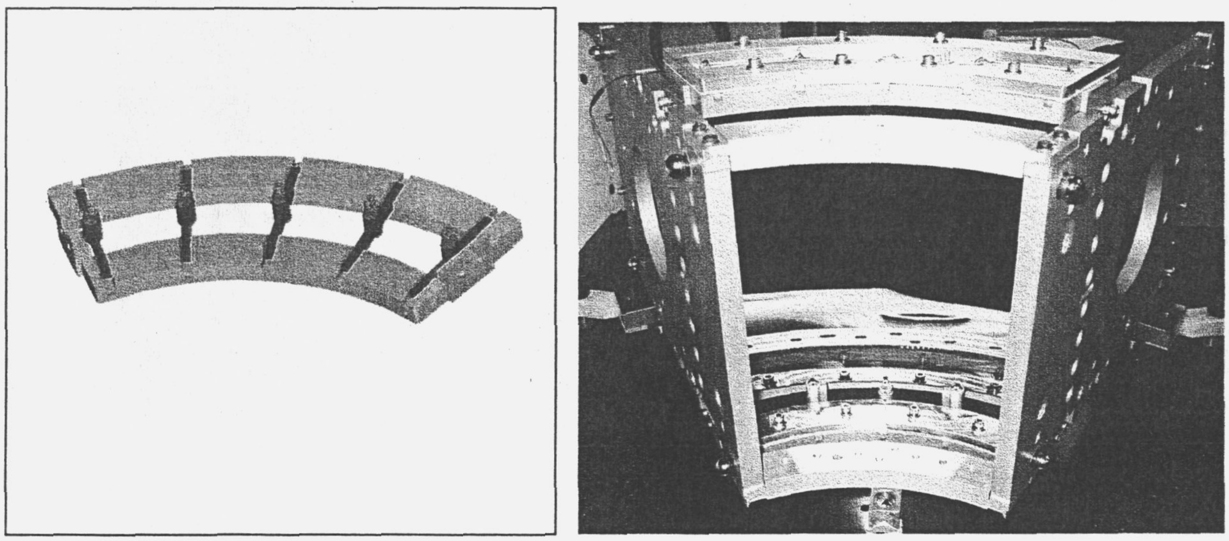

Figure 4: (Left) schematic of front or read end of holding fixture, with five piezoelectric actuators installed. (Right) Photo of mirror segment installed in actuator test structure. The top and bottom plates hold the actuators, which are not visible in this picture.

In conjunction with incorporation of the piezoelectric actuators, we have refined our alignment methodology. We still rely on the Centroid Detector Assembly (CDA), originally developed the align the much more accurate AXAF (Chandra) mirrors, as our fine alignment tool.[9] Prior to using the CDA, however, we use a collimated white light beam to view reflected light from the entire mirror surface. Observing the reflected light in a CCD allows us to quickly remove gross distortions due to noncircularity or variations in slope. The CDA does not view the entire mirror, but instead samples a small number of locations along the mirror azimuth, defined by a set of apertures, and therefore using the collimated beam is the only visual confirmation that the entire mirror segment is contributing to the image. When the CDA is subsequently employed, after the initial alignment using the collimated beam, the entire return beam from the mirror can be made to fall within the small capture range of the CDA detector. This dramatically reduces the amount of time needed to carry out the alignment of a mirror. Our alignment station is currently being reconfigured to incorporate both of these capabilities. Additionally, an interferometer will view the mirror being aligned at normal incidence, to measure axial profiles. In that way, the mirror surface is monitored during alignment, and distortions are kept to a minimum.

Figs. 5 and 6 show the outcome of the alignment of a recently produced mirror segment. In Fig. 5 we show optical CCD images of the reflected beam from a single mirror, well in front of the focus, at the focus, and behind it, before and after the piezoelectric actuators have been manipulated. The improvement of the symmetry of the image is dramatic, but still clearly far from perfect. Fig. 6 shows the result of the subsequent alignment using the CDA. The

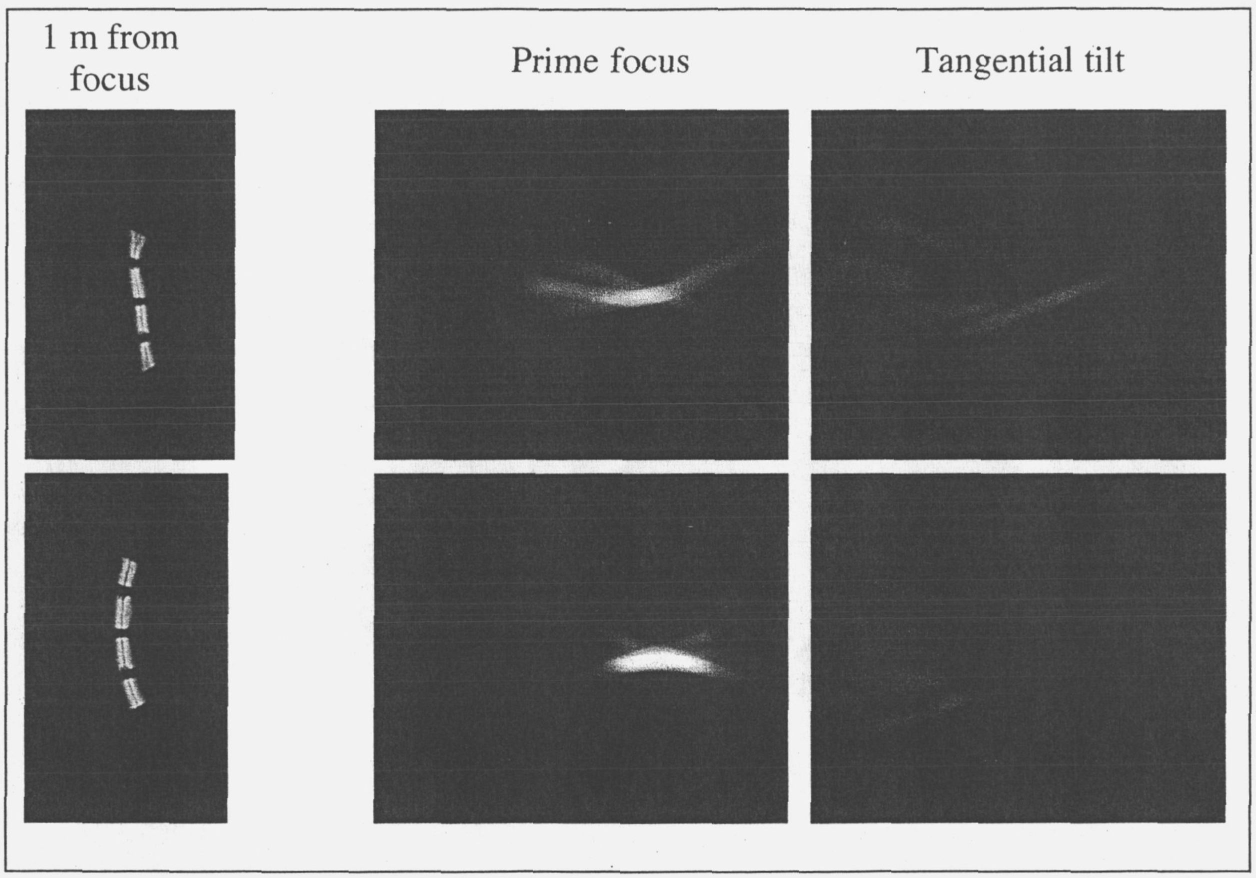

Figure 5: Images from parallel light beam reflected by a mirror segment before (top) and after (bottom) alignment using the piezoelectric actuators. The images on the left are taken 1 m in front of the nominal focus; the central images were taken at the nominal focus; the images on the right were taken behind the focus. Note that while the aligned image appears symmetric in front of the focus, it is highly asymmetric at the focus. This asymmetry can be removed via more precise alignment

left side of Fig. 6 shows the distribution of samples from the mirror surface when the mirror is taken directly from the collimated beam alignment. The right side shows the improvement possible by further manipulating the piezoelectric actuators, and monitoring the CDA output. All of the CDA samples fall within a diameter of 2 arc seconds, well within the Constellation-X alignment requirement. While this result is extremely encouraging, there is no accompanying interferometer data, so we don't know for this particular case whether the mirror surface has been distorted.

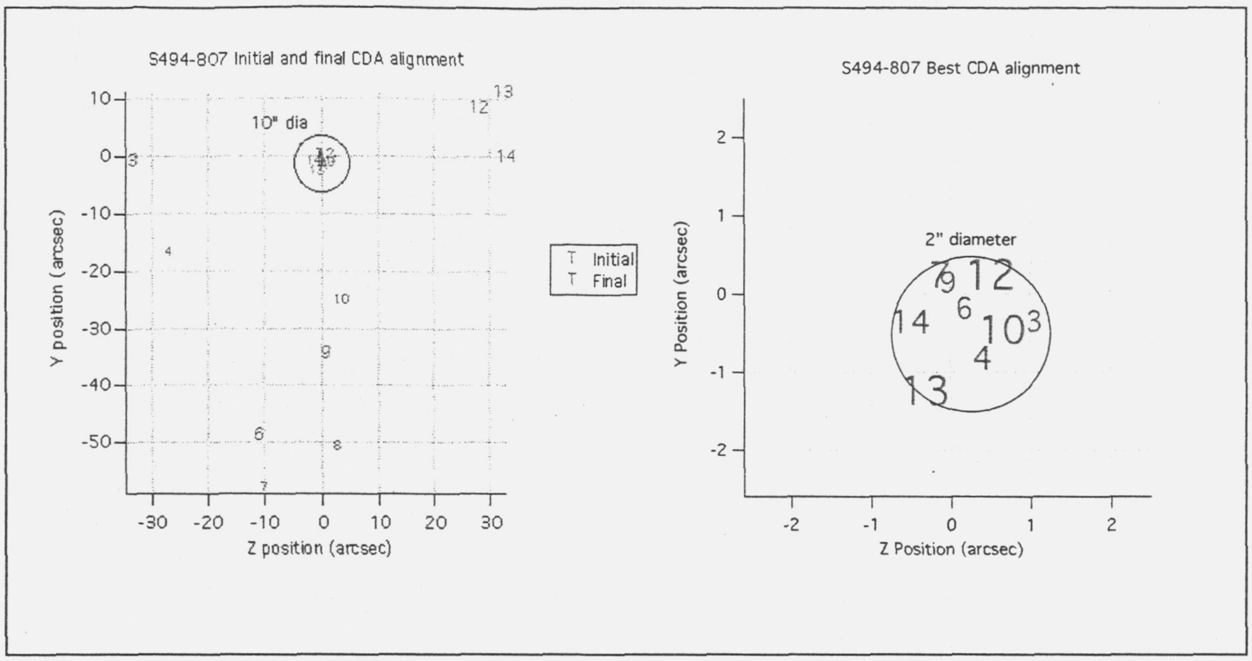

Figure 6: Results of alignment of a single mirror segment using the Centroid Detector Assembly (CDA), in conjunction with a parallel optical beam. Numbers in left figure indicate location of CDA return signals from various discrete azimuthal locations on segment after visual alignment using optical collimator. The collimator brings all the signals within the capture range of the CDA detector. Right figure shows result of using piezoelectric actuators in conjunction with the CDA. Return signals from all azimuthal positions are brought within a 2 arc second radius, consistent with the Con-X single reflector alignment requirement.

5. SUMMARY

Our key results over the past year are as follows:

- We have produced mirror substrates that meet the Con-X requirement.
- Epoxy replication is no longer needed to produce mirror segments meeting the Con-X requirement. It is unclear whether we can meet the 5 arc second HPD system performance goal without replication, so we reserve the option of restoring replication into the mirror production.
- Our knowledge of the mirror performance is limited by metrology fixturing.
- The mirror performance is limited by mandrel quality and contamination.
- We have means of performing all necessary diagnostic metrology of mirror substrates.
- We have a refined approach to aligning and mounting mirror segments, incorporating piezoelectric actuators and additional steps.
- We have shown we can align a single mirror to within the Con-X requirement.

6. NEAR TERM PLANS

As the project's evolution over the past two years have demonstrated, the SXT plans are subject to rapid change, based on available resources and Constellation-X study priorities. After a two-year delay, we are once again working towards a series of X-ray performance demonstrations. Over the next year, we plan to (i.) optically align a pair of mirror elements s to form the best possible optical image, and optically characterize the shapes of the aligned mirror elements and the imaging performance before and after bonding them; (ii.) incorporating what we learn from step (i.) align a mirror pair to higher precision, bond it to the mounting structure and perform an X-ray performance test; (iii.) add a second mirror pair in the housing to determine how well pairs can be coaligned The metrology we have performed on the mandrels will allow us to place an upper limit on the expected imaging performance of the system if all mandrel errors are removed.

In parallel with this demonstration plan we expect to make continuing process improvements on mirror forming. Most notably, we will figure one pair of mandrels to a surface quality consistent with a 5 arc second HPD mirror system. Once these become available, we will incorporate them into the test flow.

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